Results from E949

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Results for

$K^+ \to \pi^+\pi^0\gamma$
$K^+ \to \pi^+\gamma\gamma, \quad K^+ \to \pi^+\gamma$
$\pi^0 \to \nu\overline{\nu}$

E787 Collaboration

UNIVERSITY OF ALBERTA
EDMONTON, ALBERTA, CANADA

UBC

BROOKHAVEN NATIONAL LABORATORY

DEI SUB NUMINE VIGET

KEK
高エネルギー加速器研究機構

OSAKA UNIVERSITY

TRIUMF

E949 Collaboration

UNIVERSITY OF ALBERTA
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UBC

INR

BROOKHAVEN NATIONAL LABORATORY

Fermilab

National Defense Academy, Japan

KEK
高エネルギー加速器研究機構

OSAKA UNIVERSITY

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KYOTO UNIVERSITY
KYOTO JAPAN
FOUNDED 1897

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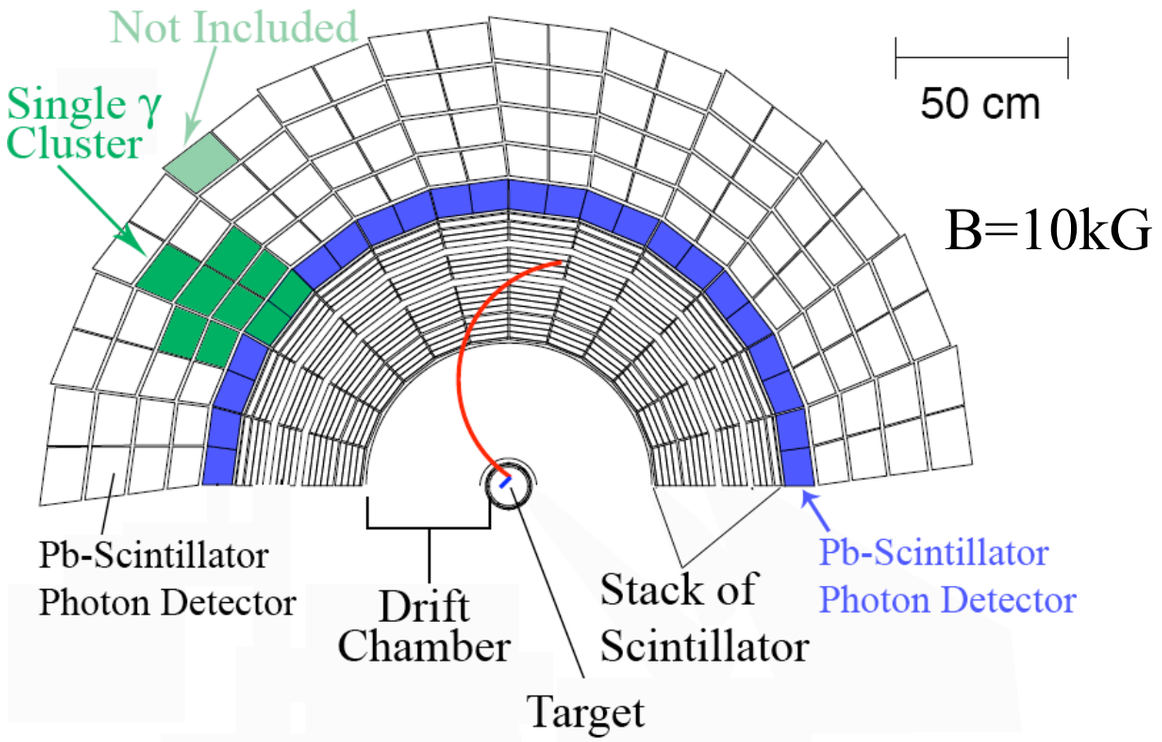
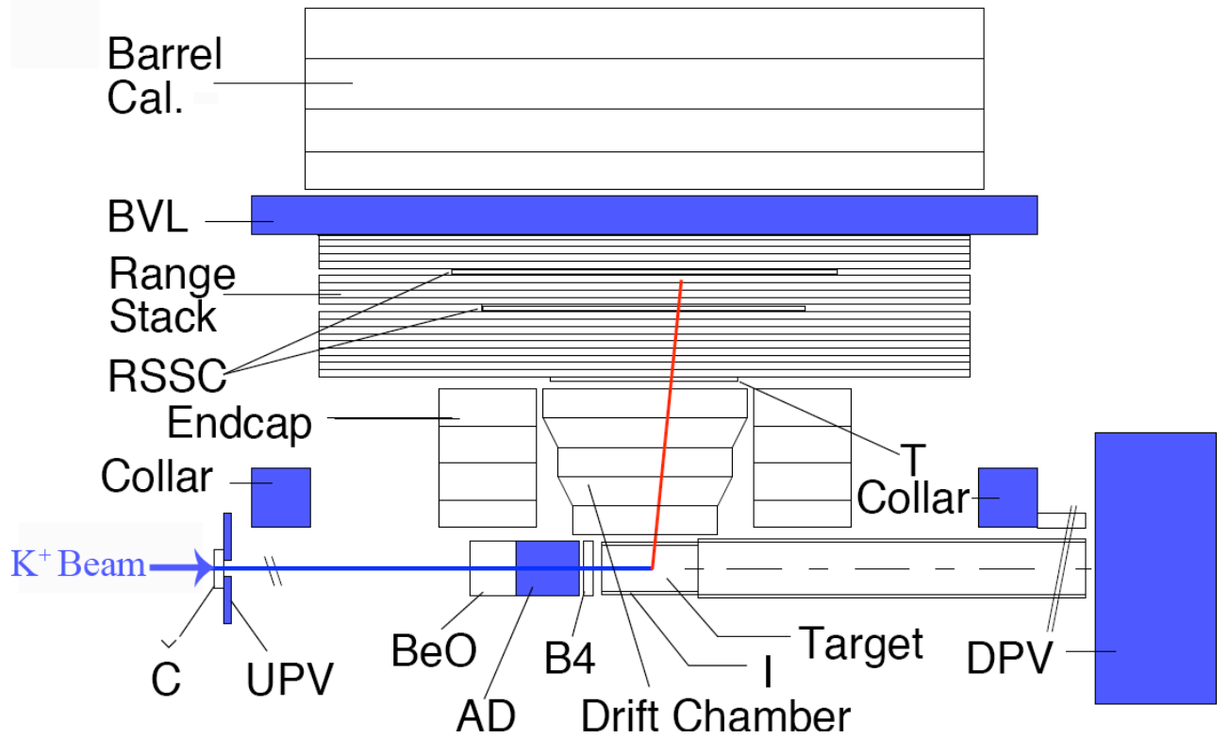
STONY BROOK
STATE UNIVERSITY OF NEW YORK

The University of New Mexico

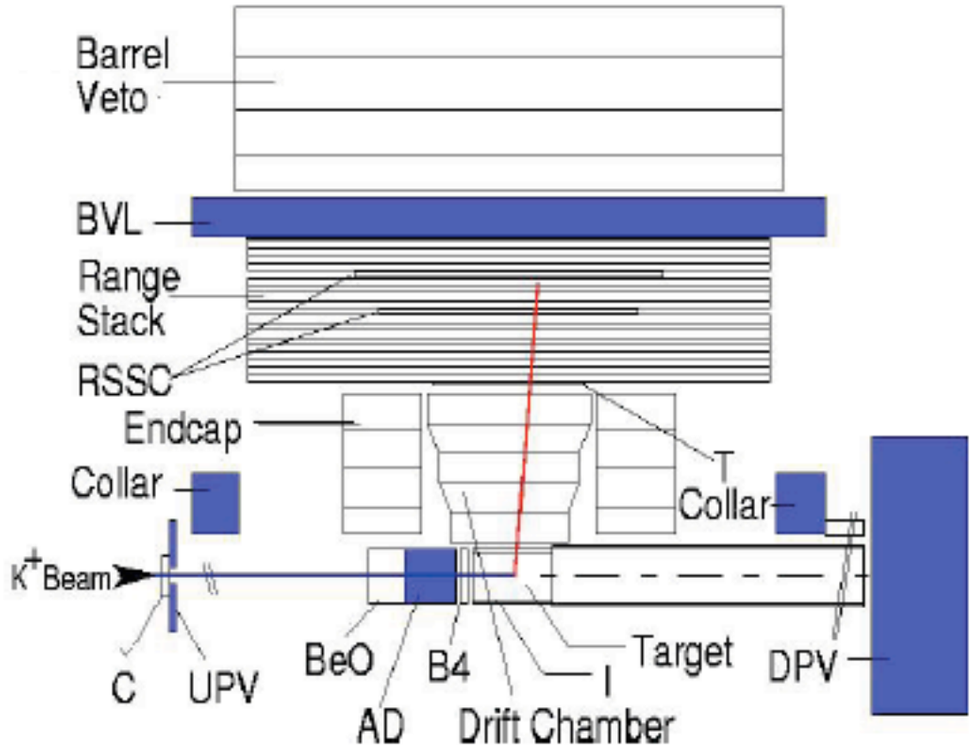
$K^+ \to \pi^+ \nu\bar{\nu}$ Detector

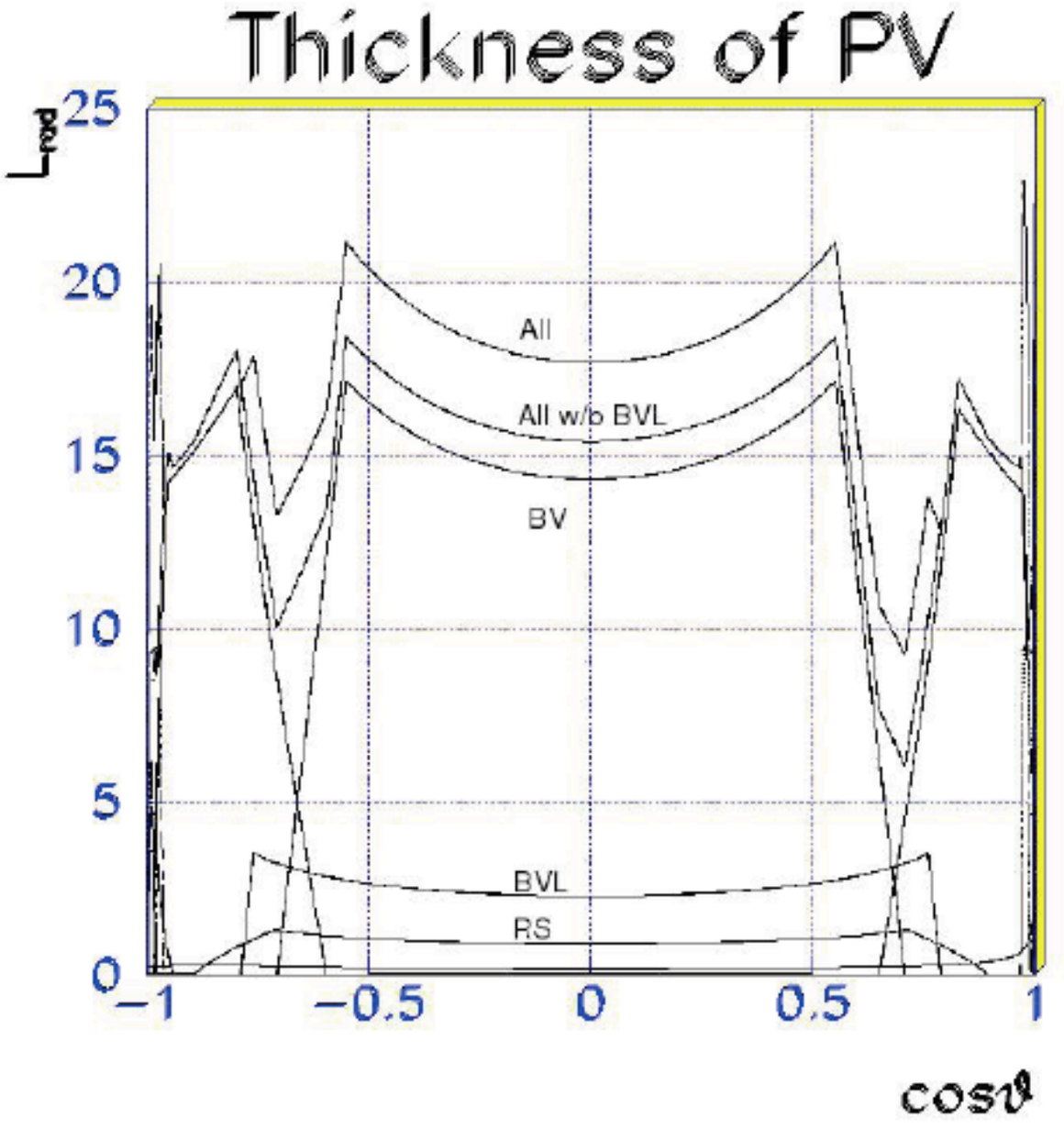




- Incoming K^+ beam: ~710 MeV/c, tagged by Čerenkov & dE/dx counters
- Decay product: 2ns delay from K^+
- Stopped decay product: Measure *Energy, Momentum, Range*.
  - Observe $\pi^+ \to \mu^+ \to e^+$ decay sequence
- Photon detection: Everywhere possible!
- One detector many possible jobs.

Photon Detectors

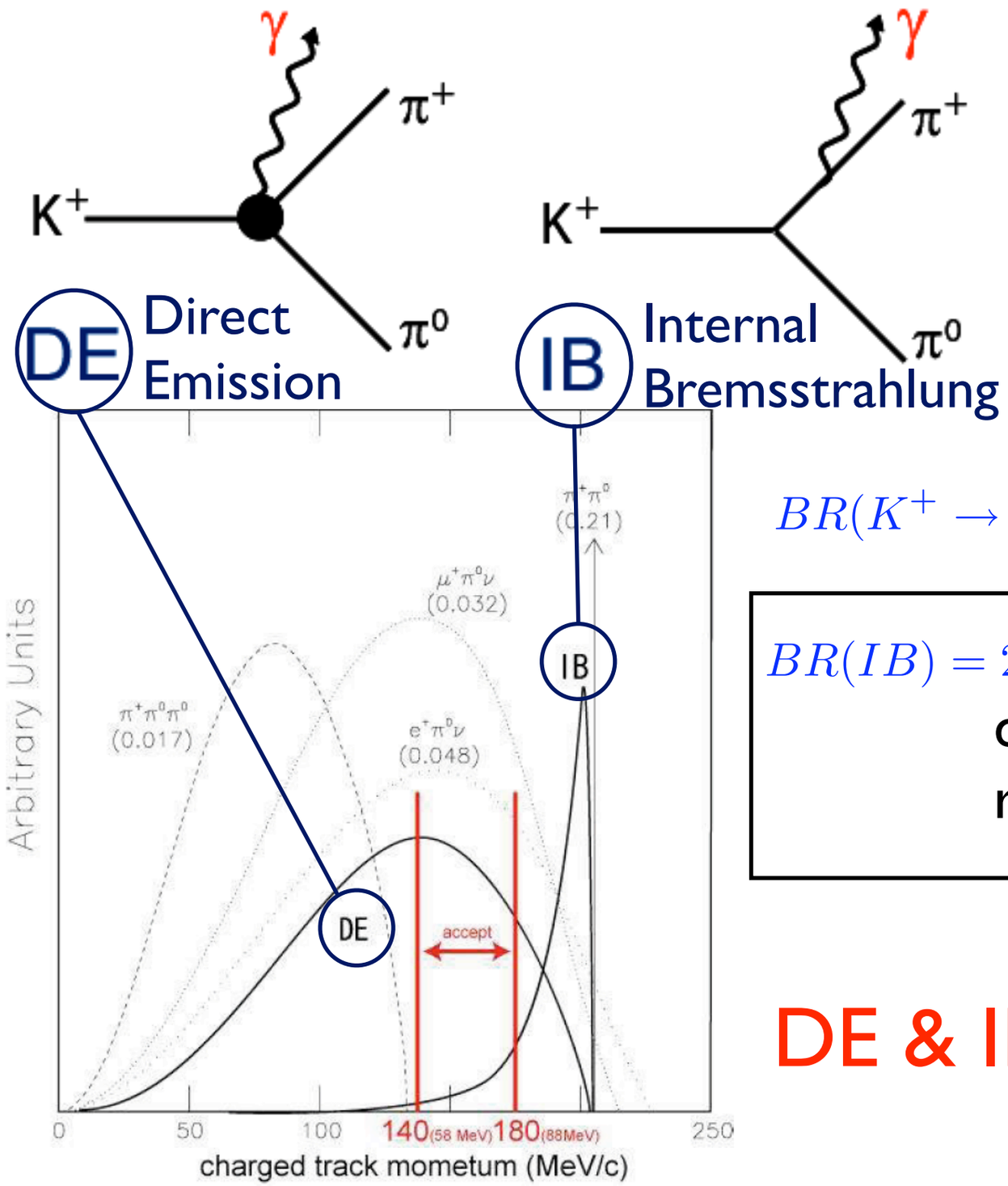




π^0 energy resolution:
$\Delta E/E \sim 0.14$ @ 246 MeV

π^0 rejection:
$\sim O(10^6)$ for $K^+ \rightarrow \pi^+\nu\nu$ analysis

$K^+ \to \pi^+\pi^0\gamma$



$$BR(K^+ \to \pi^+\pi^0\gamma) = (2.75 \pm 0.15) \times 10^{-4} \quad (PDG04)$$

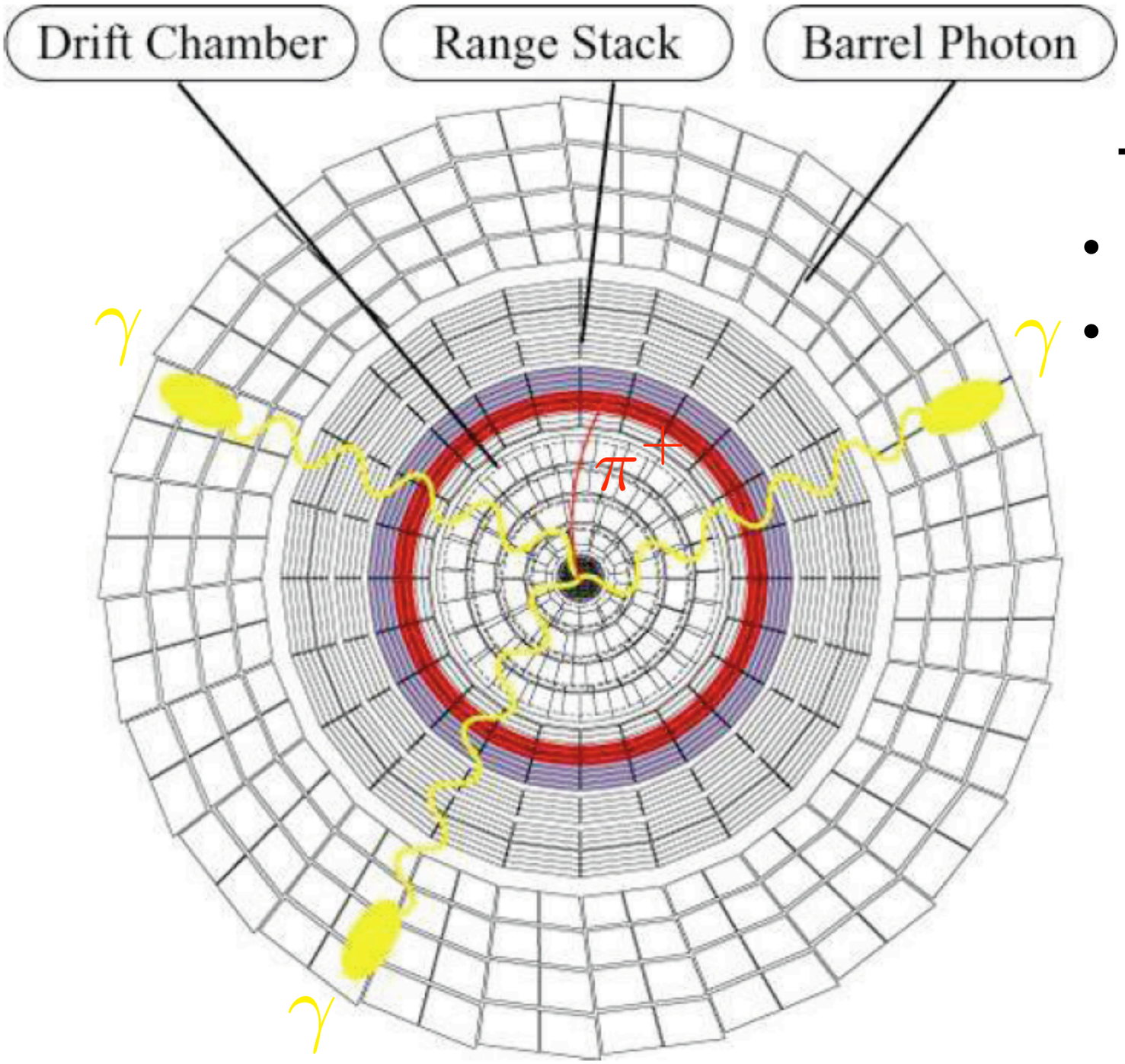
$BR(IB) = 2.61 \times 10^{-4}$

dominates QED

radiative correction to BR($K_{\pi 2}$)

DE & IB differ kinematically

$K^+ \rightarrow \pi^+\pi^0\gamma$



Trigger Requirements

- ≥3 photon clusters
- π^+ stop in RS layer 3-6 (1998)
  layers 6-10 (1995)

⇒ More Acceptance for DE than 1995

Number of kaons:

3.48×10^{11} (1998)
2.83×10^{11} (1995)

$K^+ \to \pi^+\pi^0\gamma$ *analysis*

Reconstruction

- Charged track kinematics
- Photon clustering
  - Energy & Direction
- Kinematic fit to $K^+ \to \pi^+\pi^0\gamma$

Background Estimation

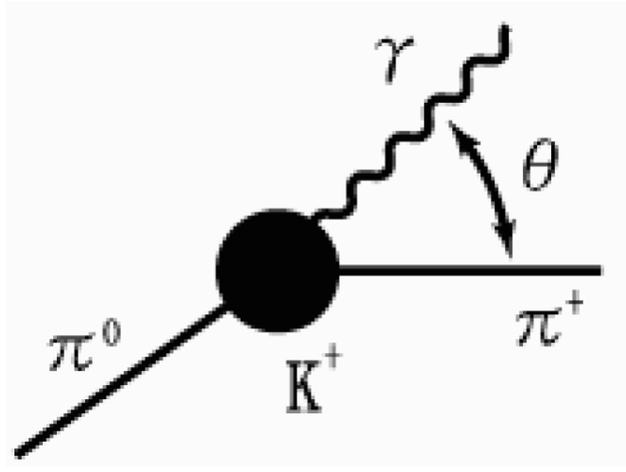
- Use "dual cut" technique like $K^+ \to \pi^+\nu\nu$ analysis
- 1.3% background in "DE region"

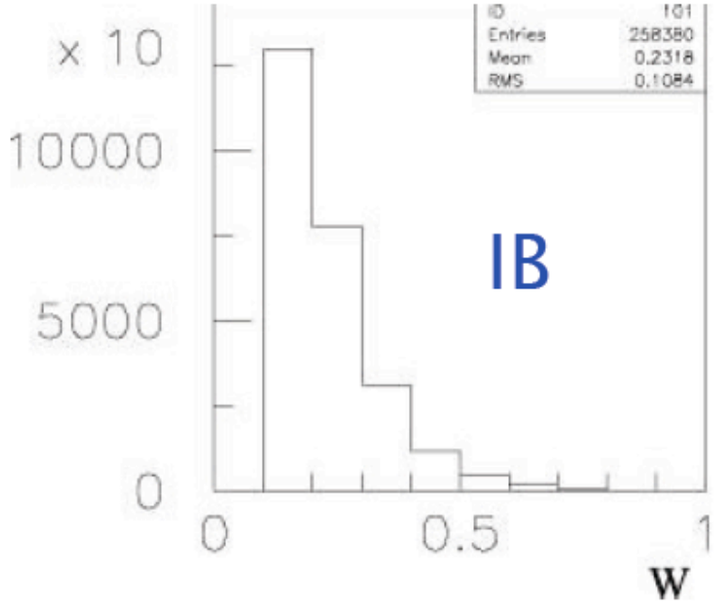
Fit to the W spectrum to extract BR(DE), using BR(IB) to normalize.

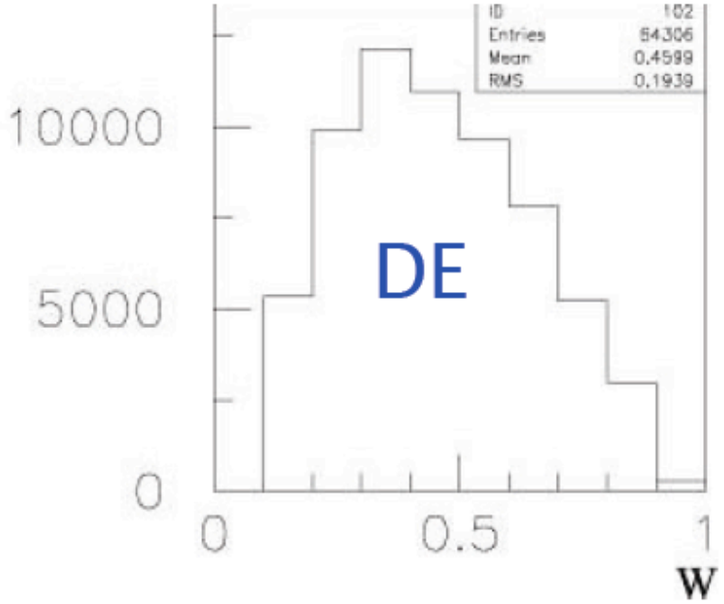
$K^+ \to \pi^+\pi^0\gamma$ *analysis*

In Kaon rest frame

$$W^2 = \frac{E_\gamma^2(E_{\pi+} - P_{\pi+} + \cos\theta_{\gamma\pi+})}{m_K m_{\pi+}^2}$$

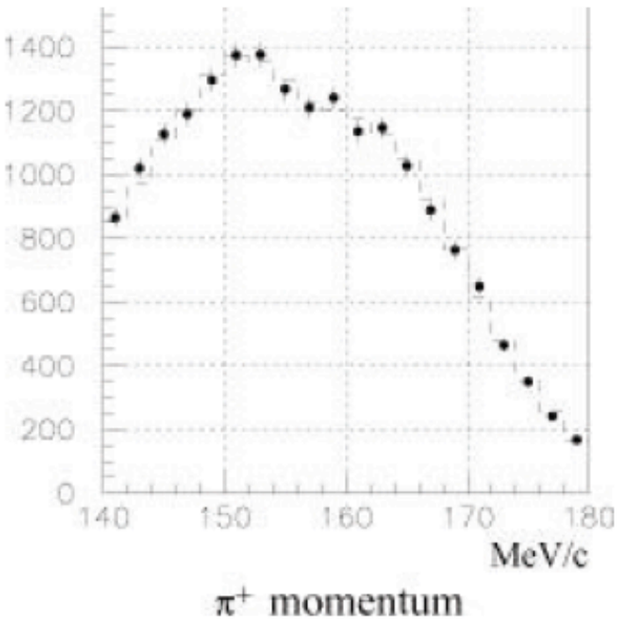




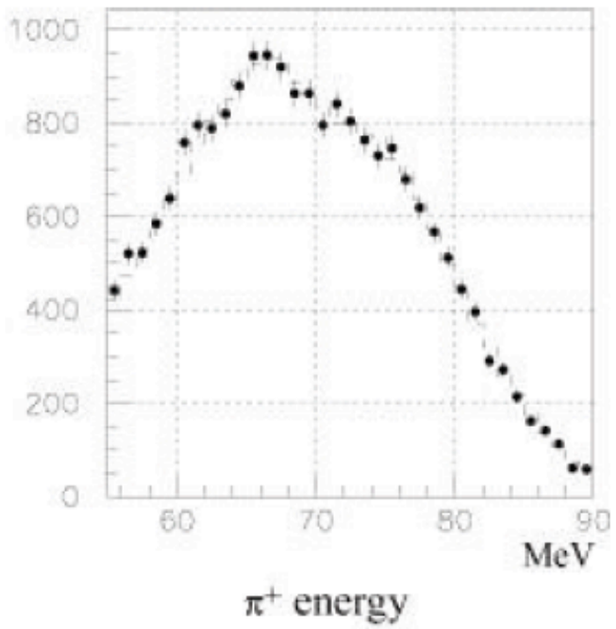


$K^+ \to \pi^+\pi^0\gamma$

Data & MC Consistency

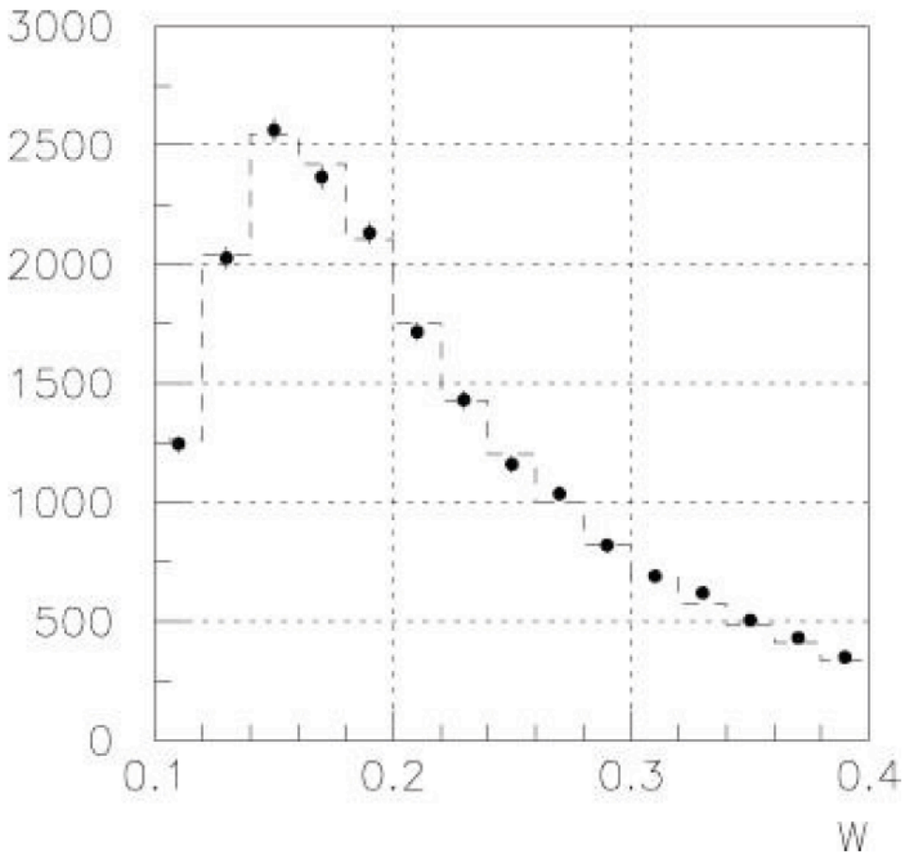


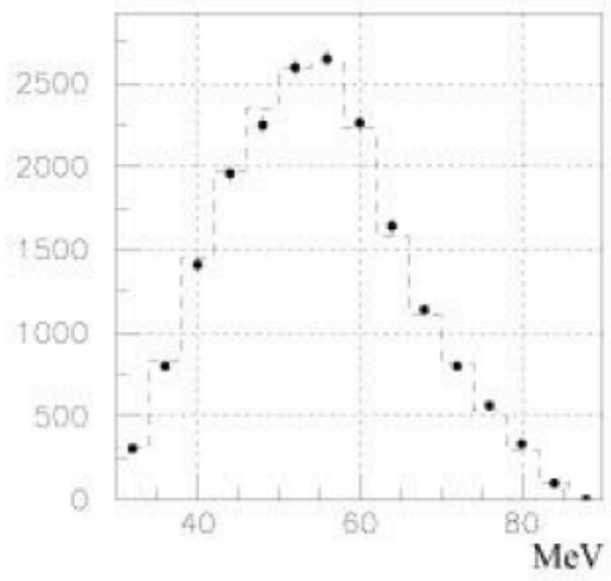
π^+ momentum



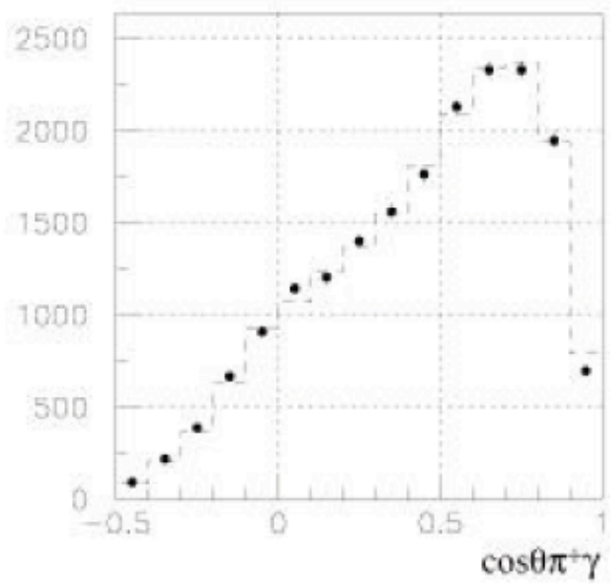
π^+ energy

Remove DE: require W<0.4





photon energy

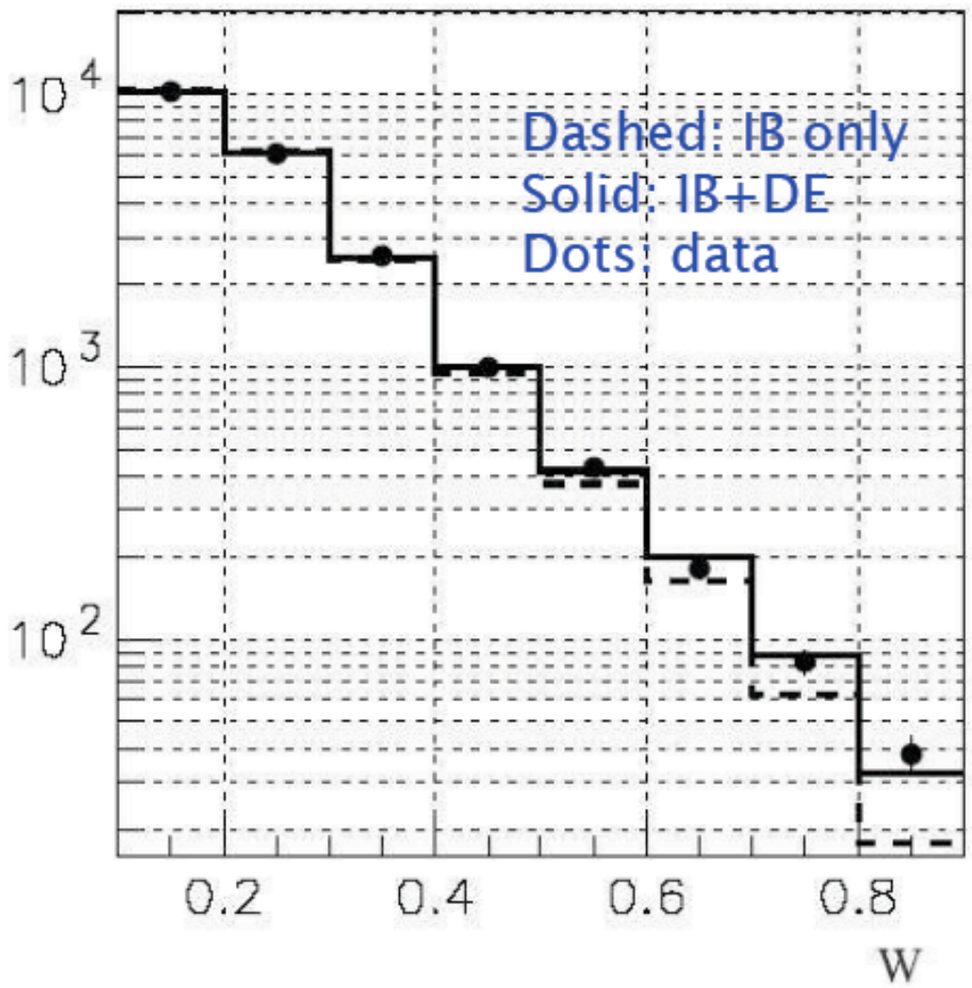


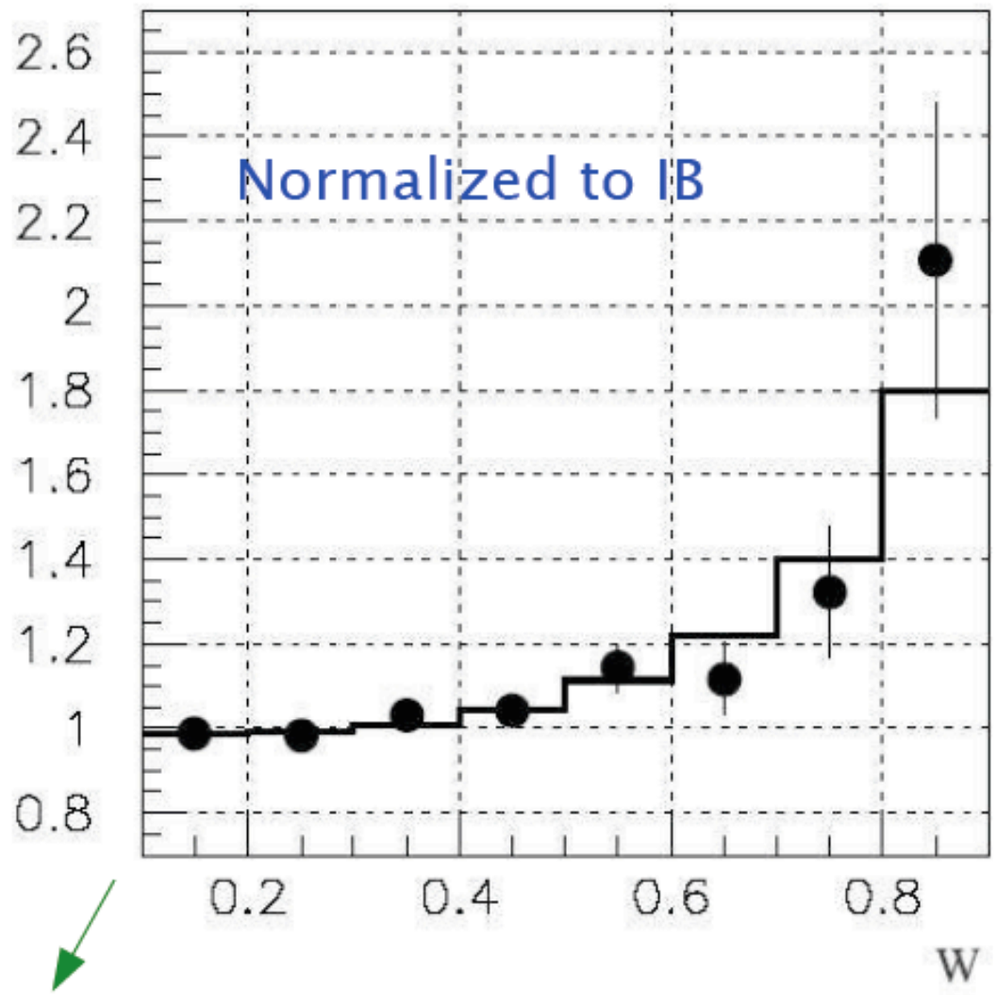
$\cos\theta\pi^+\gamma$

Dots = Data
Dashed = Monte Carlo

$K^+ \to \pi^+\pi^0\gamma$

W Spectrum





$BR(K^+ \to \pi^+ \pi^0 \gamma, DE, T(\pi^+)=(55,90)\ MeV) = (3.5 \pm 0.6\ (stat)\ ^{+0.3}_{-0.4}\ (sys)\ ) \times 10^{-6}$

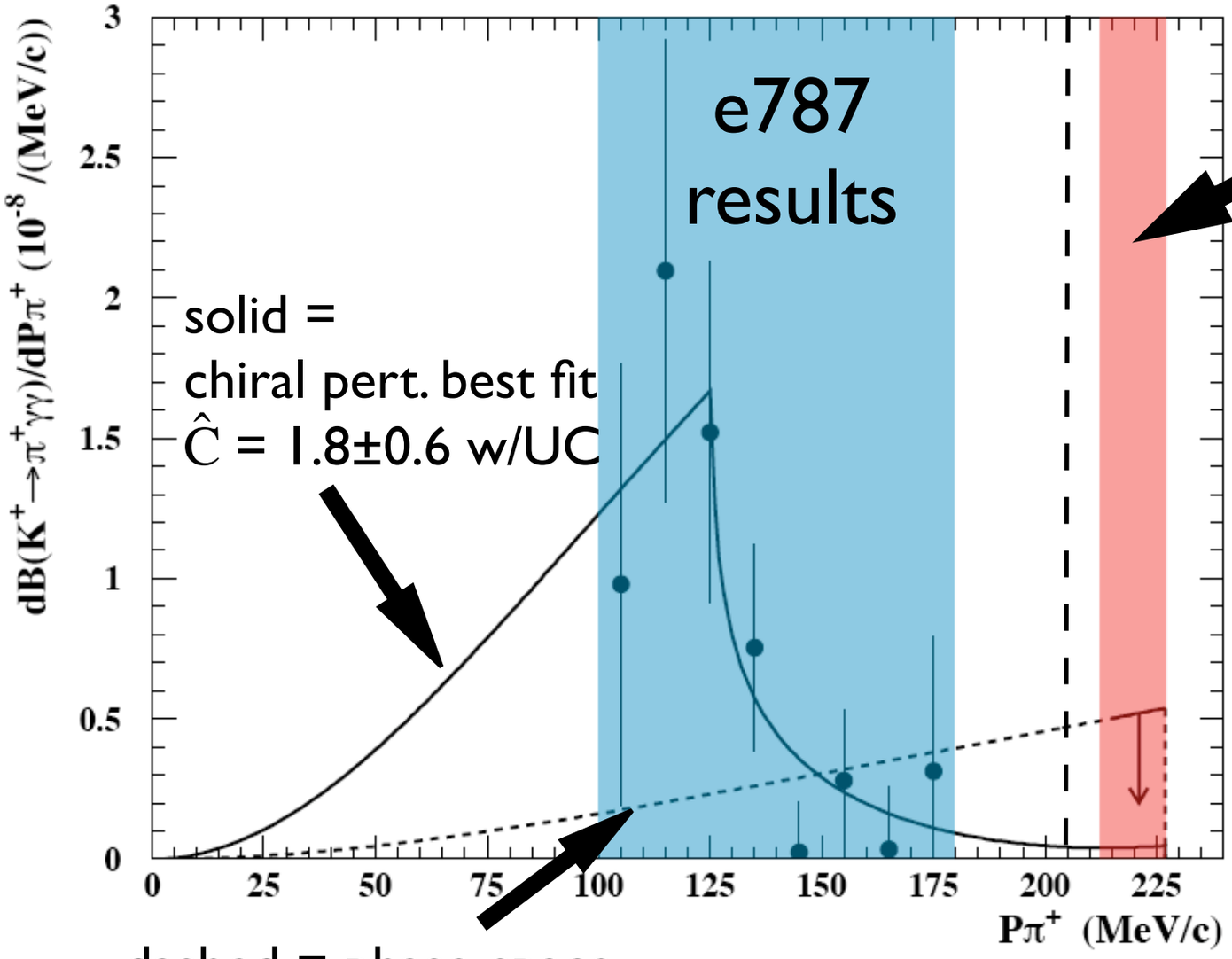
E787 (1998 data) Preliminary.

Systematic Uncertainty

Ratio of DE to IB

error source	variation	a^{DE} error
pion momentum	+0.3MeV/c	2.8%
	−0.3MeV/c	−2.4%
photon position	−2%	−4.0%
photon position resolution	+0.8cm	−3.3%
visible fraction		negligible
photon interaction		−1.4%
fitting method	the angle	+6.9%
	photon energy	−7.5%
UMC statistics	smaller sample	±2.0%
combined		+8% -10%

$K^+ \to \pi^+ \gamma\gamma$



e787 results:

31 evts, bkg of 5.1±3.3 evts

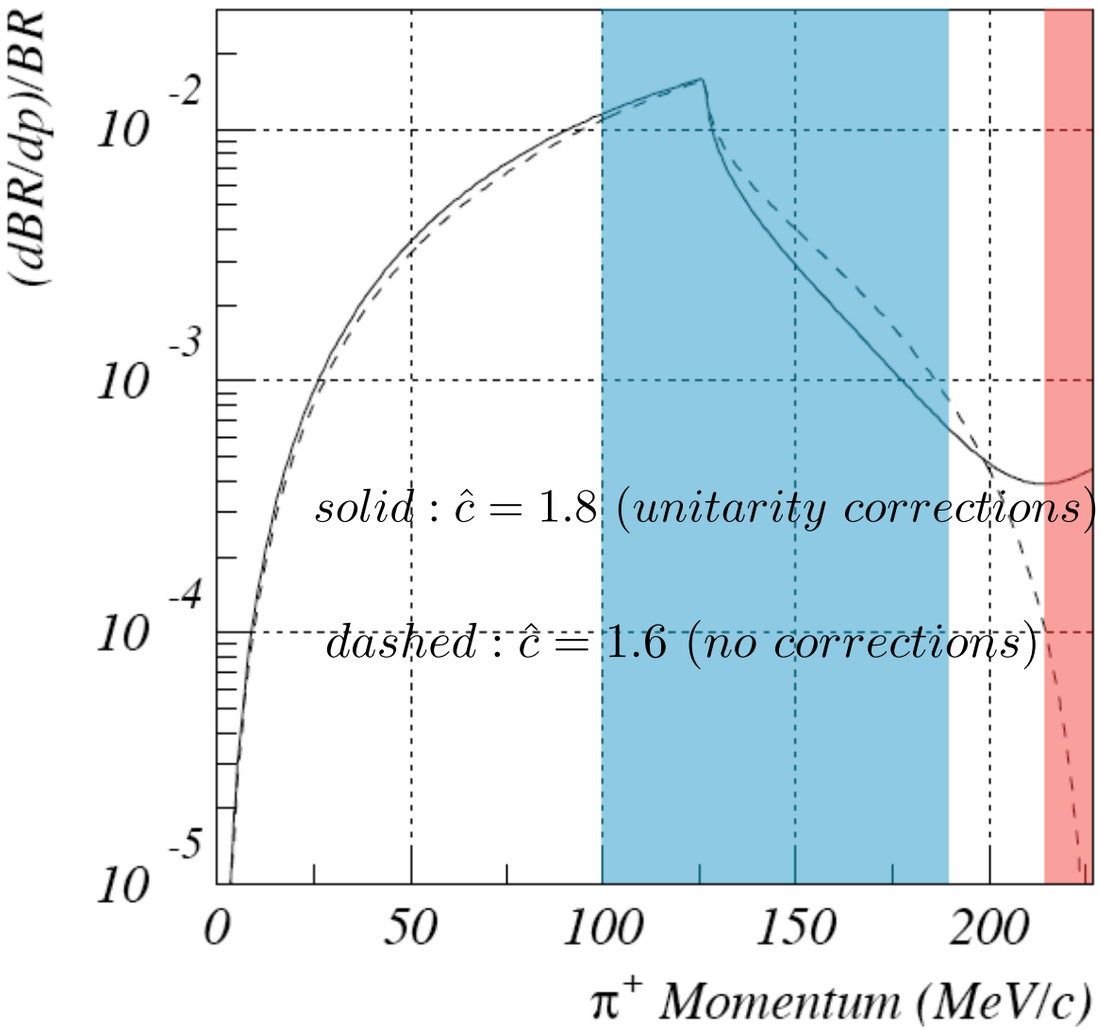
no events observed

$$BR(K^+ \to \pi^+ \gamma\gamma, P_{\pi^+} = (110, 180)\ MeV/c) = (6.0 \pm 1.5 \pm 0.7) \times 10^{-7}$$

$$BR(K^+ \to \pi^+ \gamma\gamma, P_{\pi^+} 215\ MeV/c) =< 6.1 \times 10^{-8}$$

P. Kitching *et al.*, Phys. Rev. Lett. **79**, 4079 (1997).

$K^+ \to \pi^+ \gamma\gamma$



- O(p4) in ChPT, BR & spectrum shape depend on ĉ parameter.
  - Curves similar < 200 MeV/c
  - Curves diverge >200 MeV/c
-
- Finite BR at kinematic end point using unitary corrections.
  - Ideal region for E949 to attack

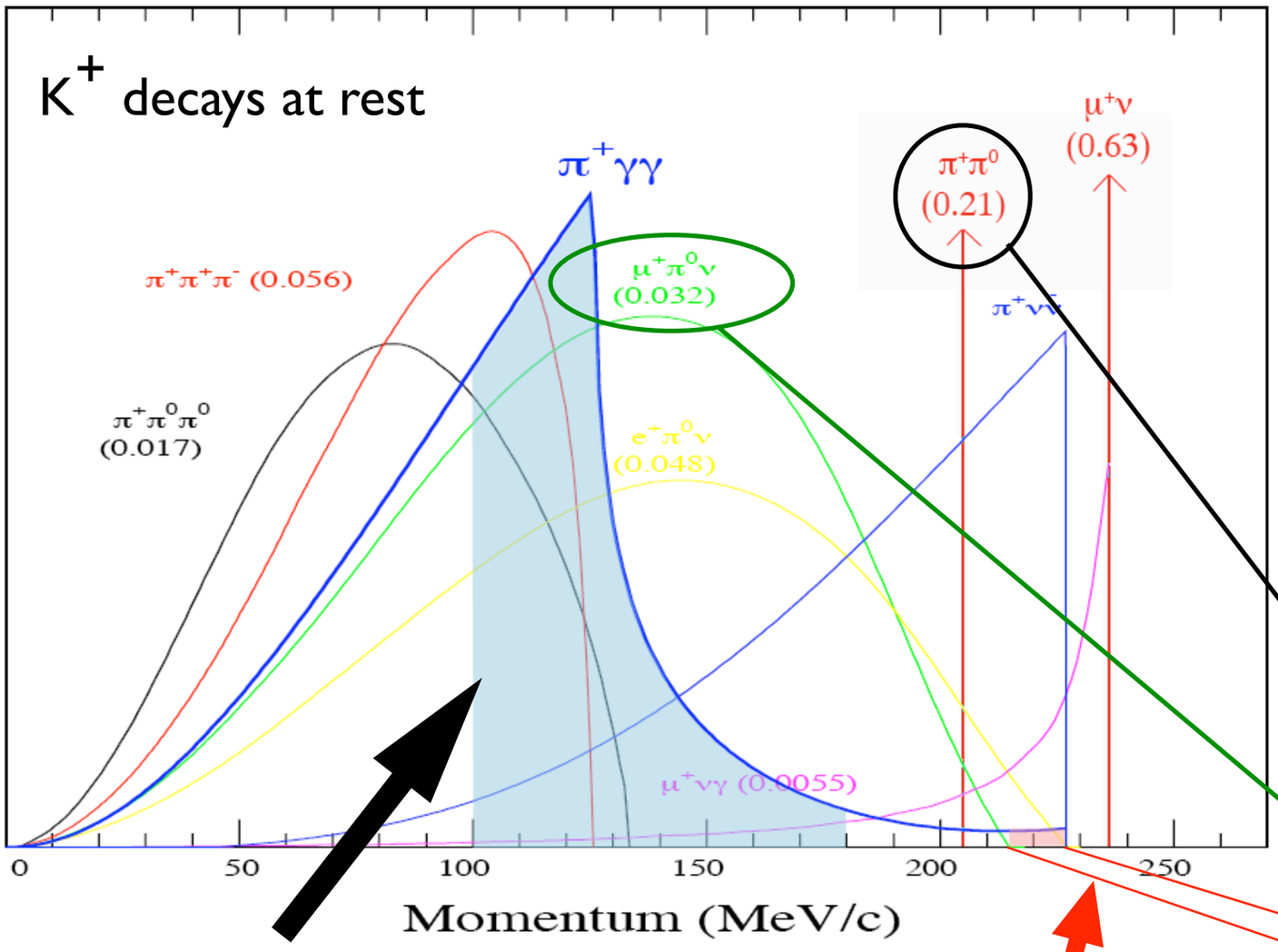
Values obtained from E787

$$\hat{c}_{No\ corr.} = 1.6 \Longrightarrow \mathcal{B}(P_{\pi^+} > 213 MeV/c) = 4.9 \times 10^{-10}$$
$$\hat{c}_{unitarity\ corr.} = 1.8 \Longrightarrow \mathcal{B}(P_{\pi^+} > 213 MeV/c) = 6.1 \times 10^{-9}$$

Order of Magnitude Different!

$K^+ \to \pi^+\gamma\gamma$

Backgrounds & Trigger Events



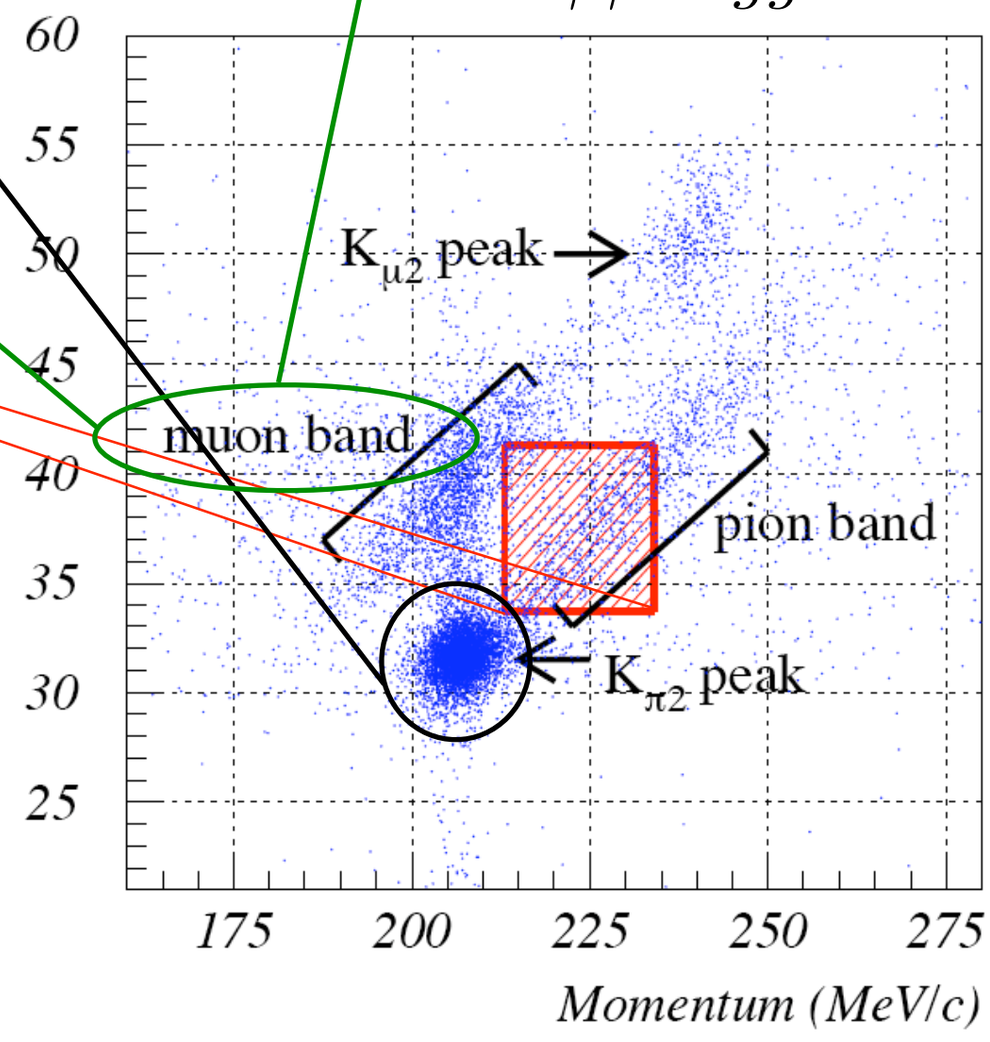
E787 Signal Region

E949 Signal Region

Background from $K^+ \to \pi^+\pi^0$

$K^+ \to \mu^+\nu\gamma$

$K^+ \to \mu^+\pi^0\nu$



$K^+ \to \pi^+\pi^0; \pi^0 \to \gamma\gamma$

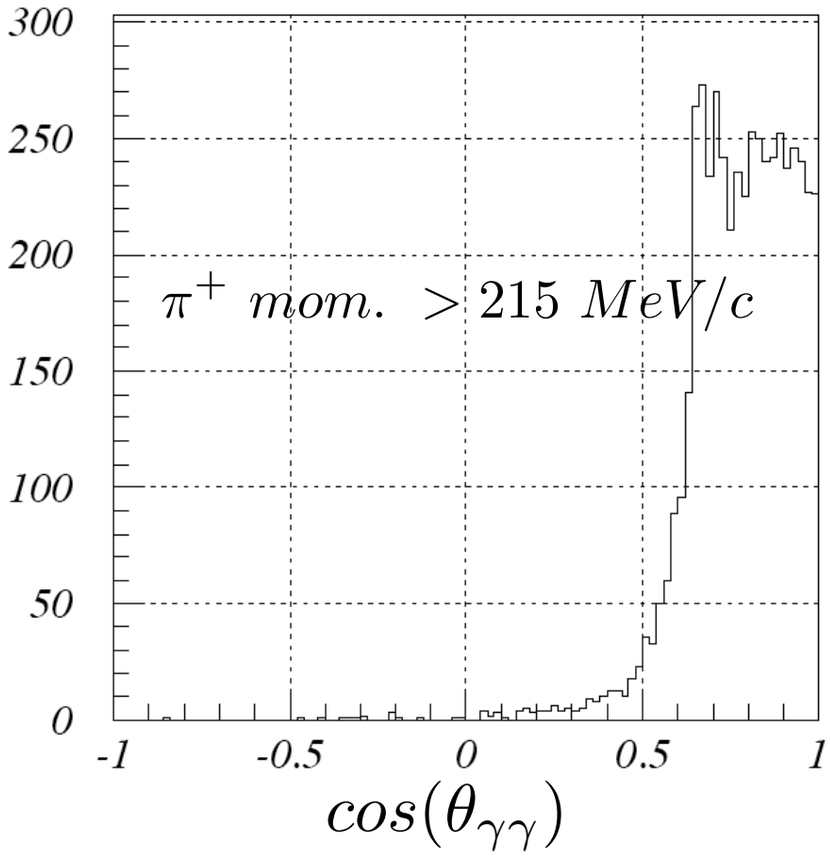
SAME FINAL STATE!

$K^+ \to \pi^+\pi^0$ *Background*

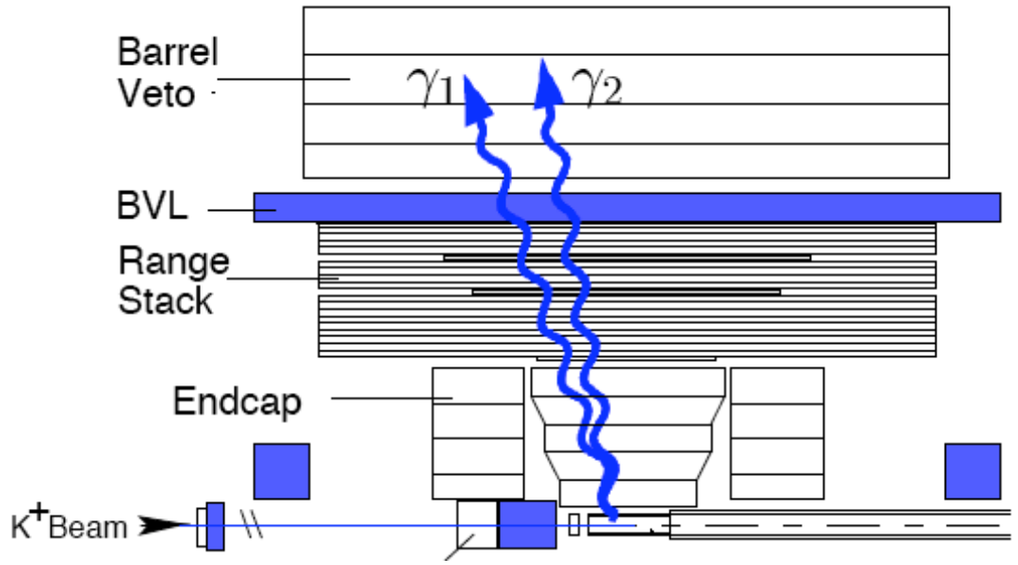
Suppress backgrounds

- *Use* π^+ *kinematics*
- *Opening angle cut on* γs

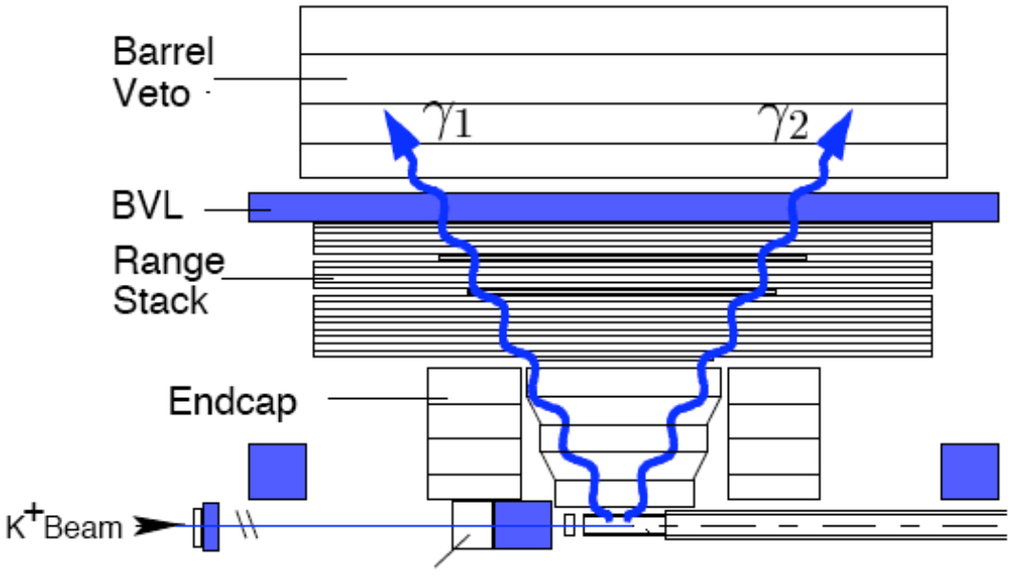
$K^+ \to \pi^+\gamma\gamma$ *Monte Carlo*



$K^+ \to \pi^+\gamma\gamma$ *signal*

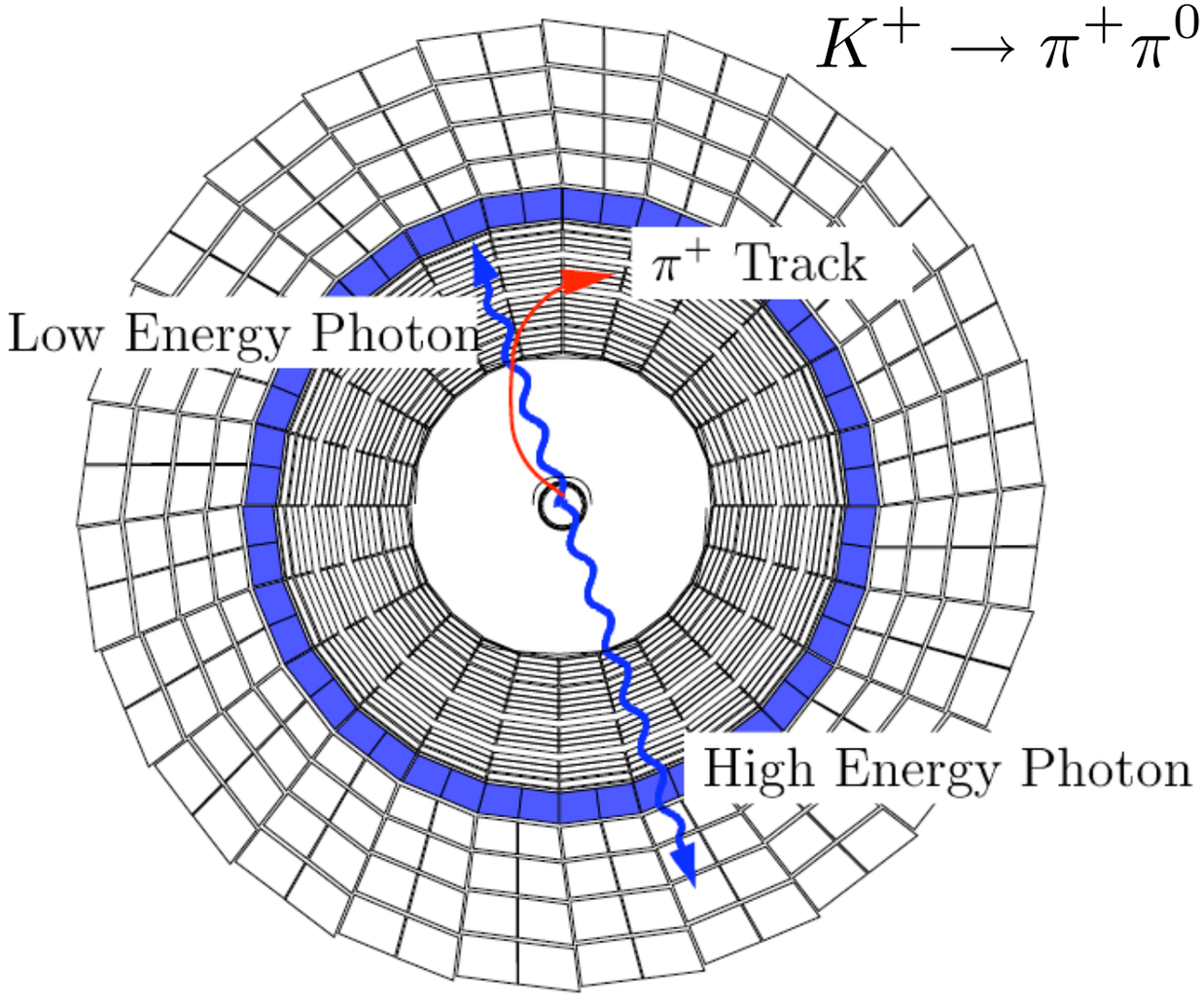


background from $K^+ \to \pi^+\pi^0$



$K^+ \to \pi^+\gamma\gamma$ Overlapping γ Background

- Cut on overlapping γ by observing larger than expected energy.



Background and Acceptance

$K^+ \to \pi^+ \nu\nu$ Technique

- Signal box blinded.
- Background estimated using "dual cut" technique.
- 1/3 data is used in setting cuts.
- Apply fixed cut to remaining 2/3 for unbiased estimate.
- Background estimates are checked by comparing prediction to observation near signal region.
- Acceptance measured from data if possible. MC used for trigger, fiducial cuts, phase space, γ reconstruction & PV cuts that depend on kinematics.

Background

Background	Background level
$K^+ \to \pi^+\pi^0$	0.017 ± 0.006
$Overlapping\ \gamma$	0.065 ± 0.065
Muon	0.090 ± 0.020
Single Beam	0.025 ± 0.014
Double Beam	$0.006\ (90\%\ C.L.)$
Total	0.197 ± 0.070

Acceptance $A^{\pi^+\gamma\gamma}_{O(p^6)} = 1.550 \pm 0.034 \times 10^{-4}$

Expected Number of Events **1.6**

(assuming unitarity corrections)

Results

Background	w/UC ĉ=1.8	w/o UC ĉ=1.6
Total acceptance	$(2.99\pm0.07) \times 10^{-4}$	$(1.10\pm0.04) \times 10^{-4}$
N_{kaon}	1.19×10^{12}	
K^+ stopping efficiency	0.754 ± 0.124	
Single Event Sensitivity	$(3.72\pm0.14) \times 10^{-9}$	$(10.1\pm0.5) \times 10^{-9}$
BR ($P_{\pi^+} > 213$)	6.10×10^{-9}	0.49×10^{-9}
Expected	1.6 events	0.05 events

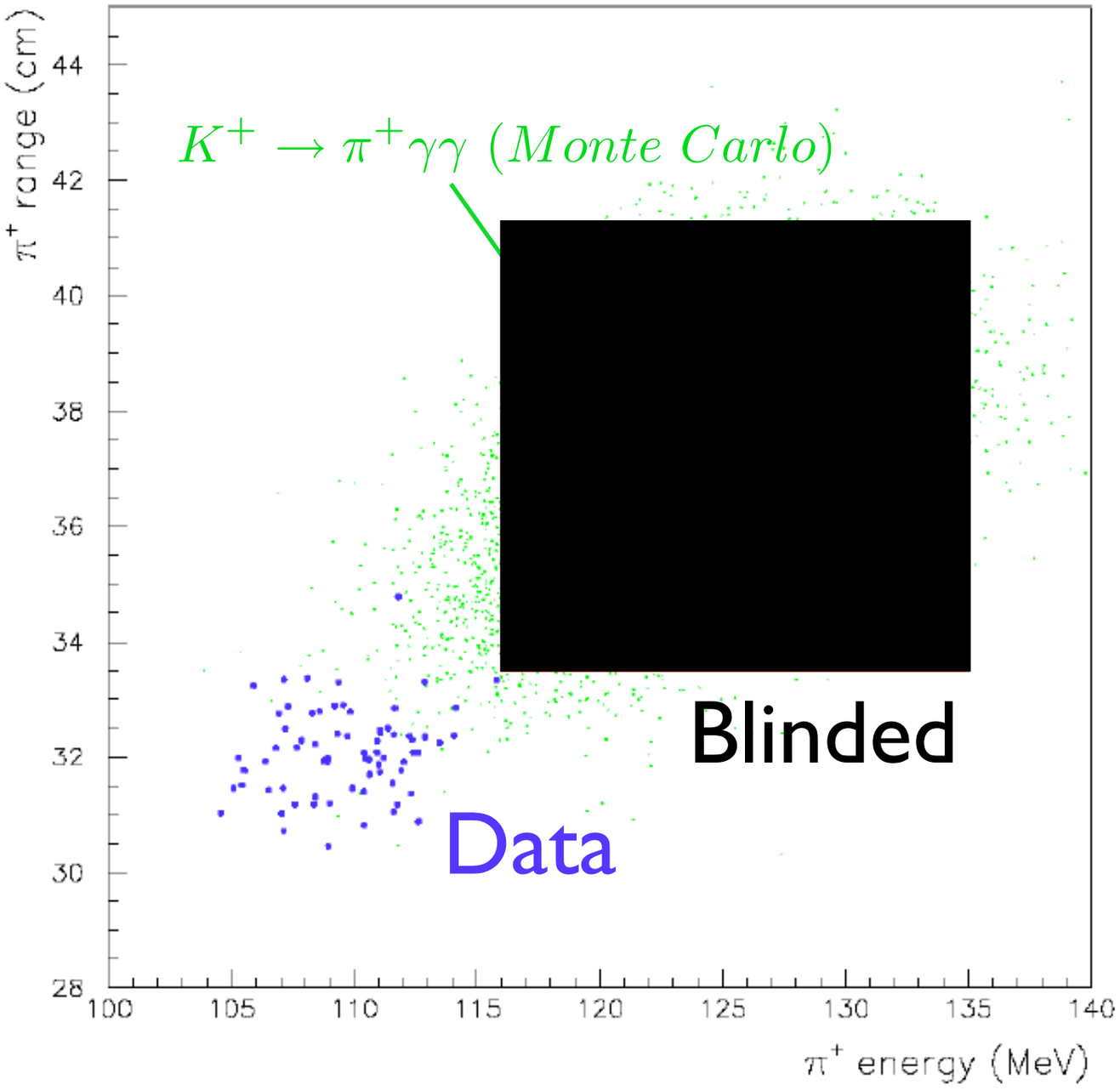
Acceptance $A^{\pi^+\gamma\gamma}_{O(p^6)} = 1.550 \pm 0.034 \times 10^{-4}$

Expected Number of Events **1.6**

(assuming unitarity corrections)

Results

E949 2002 data



ChPT w/ unitarity corrections (ĉ=1.8)

$$BR(K^+ \to \pi^+\gamma\gamma) < 8.3 \times 10^{-9}\ (90\%\ CL)$$

$$P_{\pi^+} > 213\ MeV/c$$

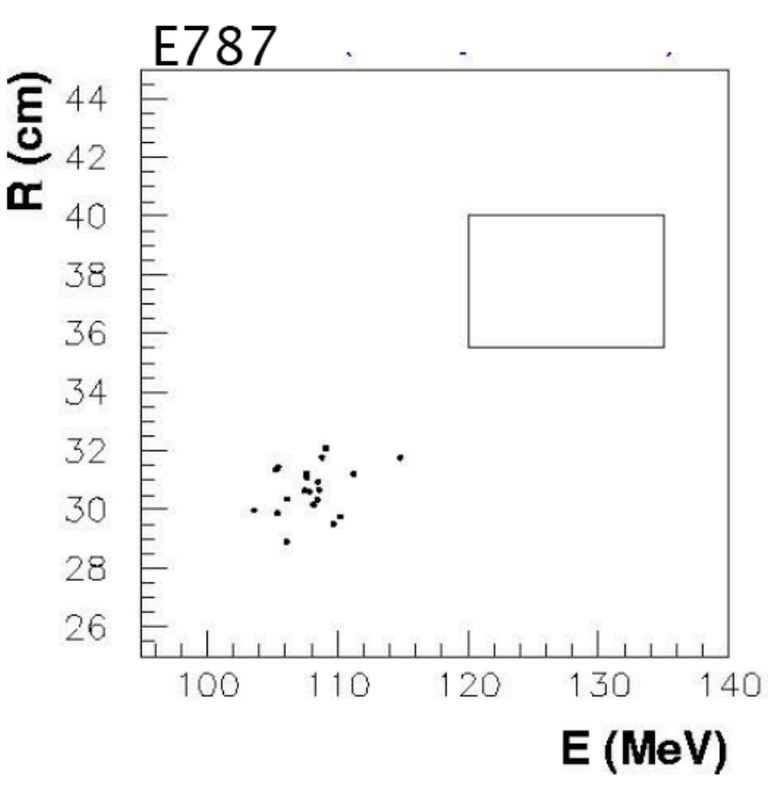
ChPT w/o unitarity corrections (ĉ=1.6)

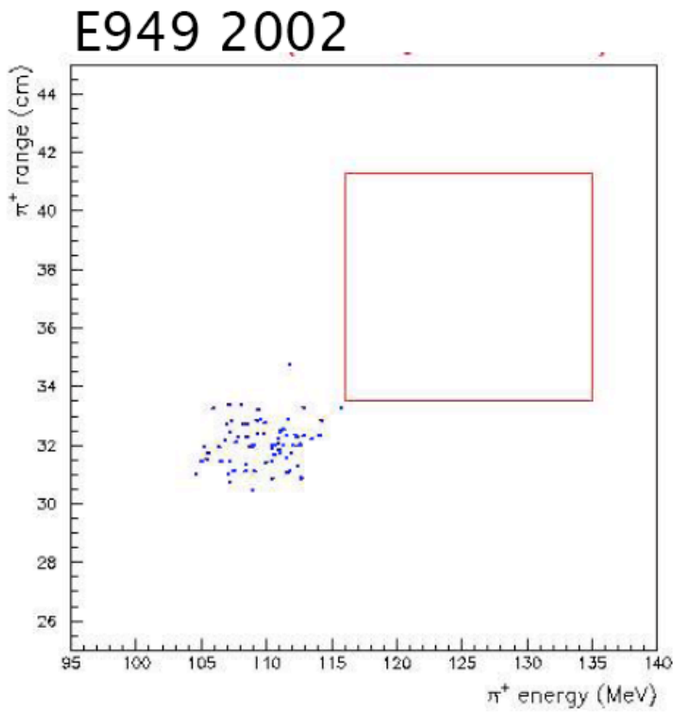
$$BR(K^+ \to \pi^+\gamma\gamma) < 2.3 \times 10^{-8}\ (90\%\ CL)$$

Results consist with and without unitarity corrections.

$K^+ \to \pi^+ \gamma$

- Same dataset as for $K^+ \to \pi^+ \gamma\gamma$ was used to search for $K^+ \to \pi^+ \gamma$
- $K^+ \to \pi^+ \gamma$ is forbidden by angular-momentum conservation and gauge invariance, but is allowed in exotic modes such as non-commutative QED.





$$BR(K^+ \to \pi^+ \gamma) < 2.3 \times 10^{-9}$$
$$(90\%\ CL)$$

$\pi^0 \longrightarrow \nu\overline{\nu}$

- Forbidden by angular momentum conservation if neutrinos are massless.

$$BR(\pi^0 \to \nu\overline{\nu}) < 5 \times 10^{-10} \; for \; m(\nu_\tau) < 18.2 \; MeV/c^2$$

- $$BR(\pi^0 \to \nu\overline{\nu}) < 1.1 \times 10^{-9} \; for \; m(\nu_\tau) < 18.2 \; MeV/c^2$$

- Experimental limit set by E787:

$$BR(\pi^0 \to \nu\overline{\nu}) < 8.3 \times 10^{-7} \; (90\% \; CL)$$

-

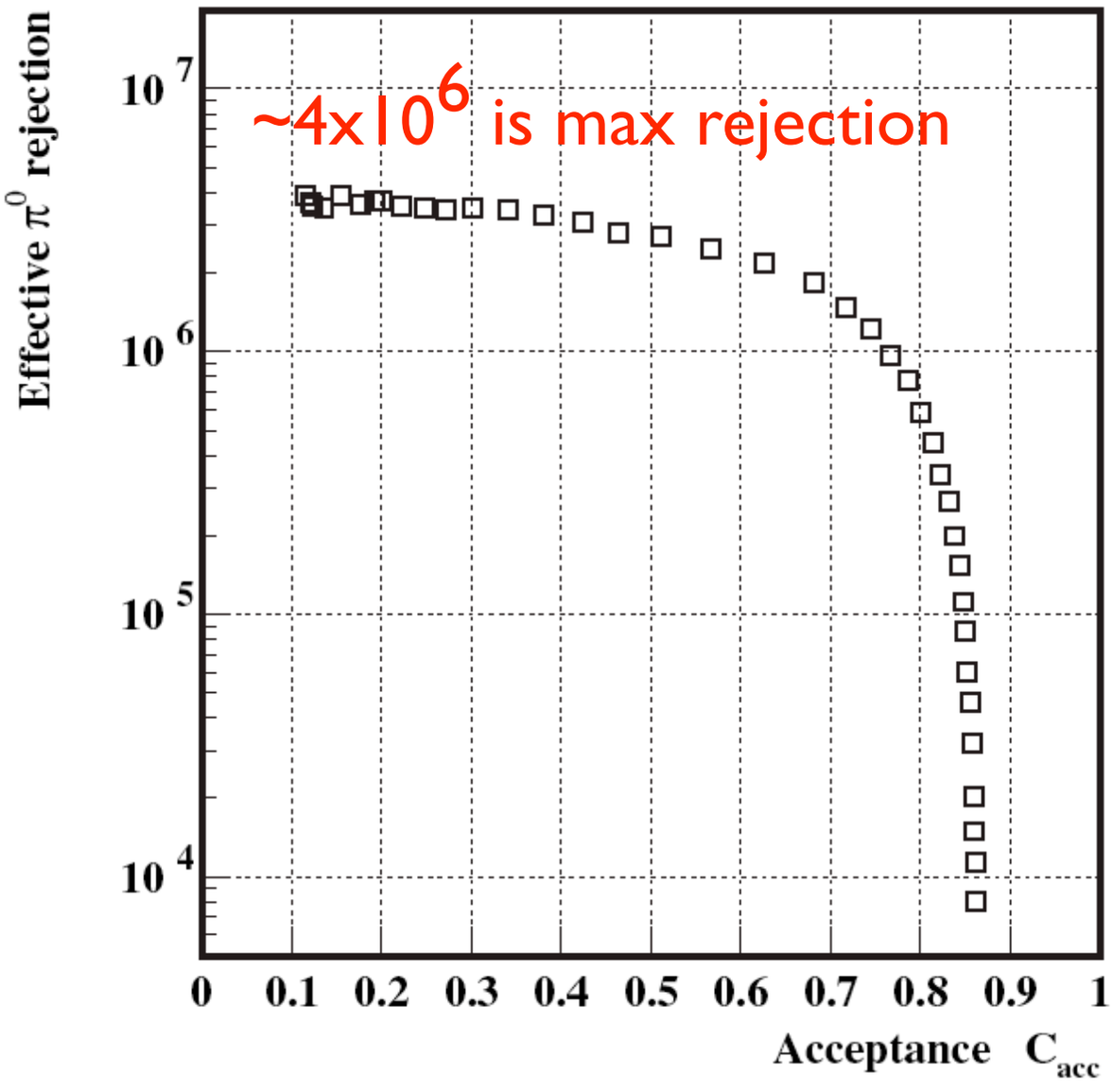
- Method: copious supply of π^0 from $K^+ \to \pi^+\pi^0$ cleanly tagged by monochromatic π^+. Look for $K_{\pi 2}$ events with no activity other than K^+ and π^+.

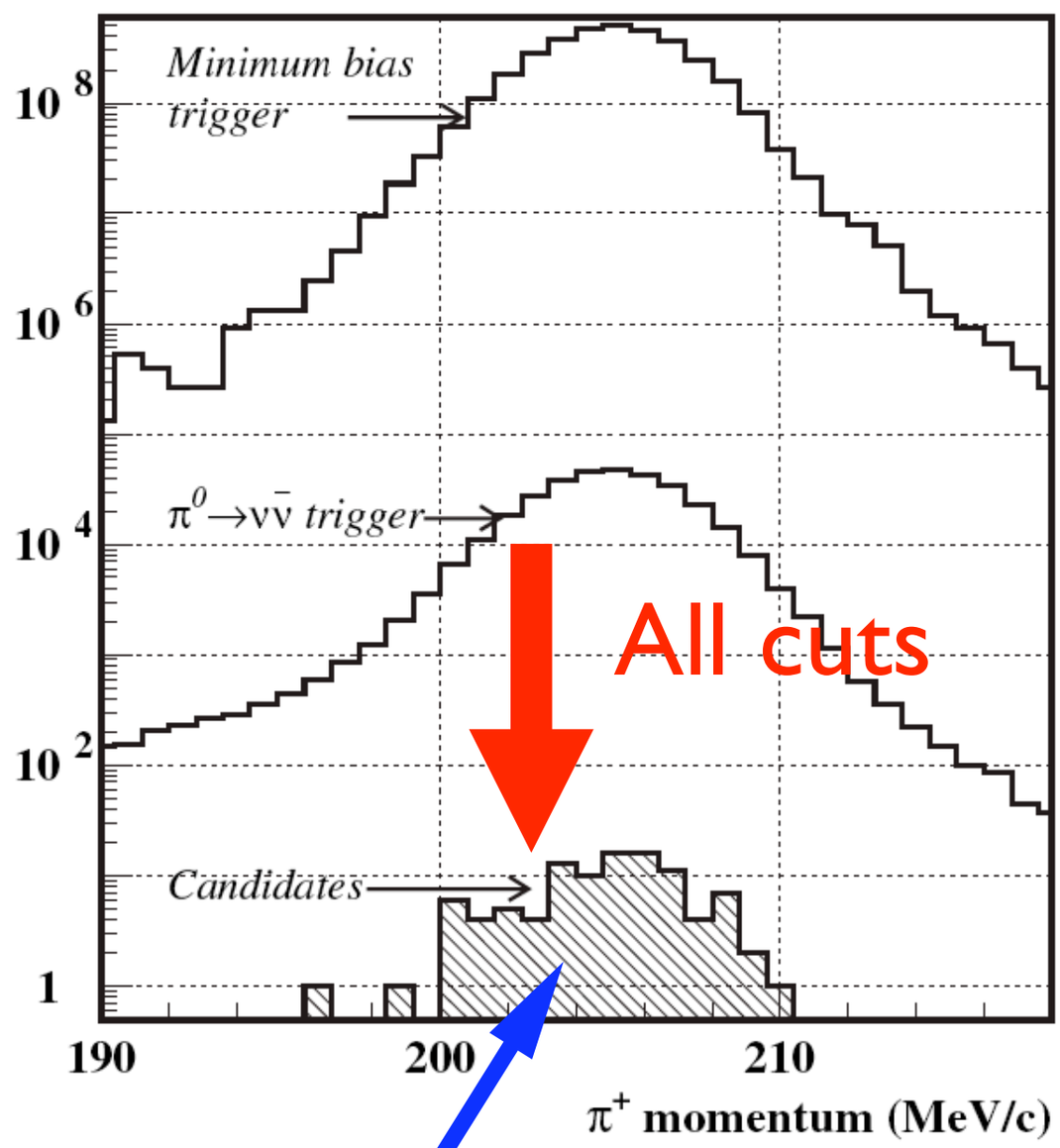
- Trigger: same as $K^+ \to \pi^+\nu\nu$. Select $K_{\pi 2}$ events & Apply the tightest photon veto.

- Tune photon veto on 1/3 of the data. Use 2/3 of the data for the $\pi^0 \longrightarrow \nu\overline{\nu}$ search.

π^0 rejection

Rej x Acc





$\pi^0 \to \nu\overline{\nu}$ result

- Failure to detect photons from π^0 are due to sampling fluctuations in electromagnetic shower of low energy photons ~20 MeV & photonuclear interactions undetected products.
- Photon detection inefficiency in E949 not fully understood.
  - Do not subtract this background.
- Treat the 99 events as candidates, we obtain
- $$BR(\pi^0 \to \nu\overline{\nu}) < 2.7 \times 10^{-7}\ (90\%\ CL)$$
- 3X improvement over previous results.

Conclusions

- E949, although optimized for $K^+ \to \pi^+ \nu\nu$, is sensitive to a number of other rare decay modes, particularly those involving photons.
- From E787 (1998 data)
- $BR_{DE}(K^+ \to \pi^+\pi^0\gamma, T_{\pi^+} = (55, 90) MeV) = (3.5 \pm 0.6\ ^{+0.3}_{-0.4}) \times 10^{-6}$
- From E949 (2002 data)
- $BR(K^+ \to \pi^+\gamma\gamma) < 8.3 \times 10^{-9}\ (90\%\ CL)\ \ P_{\pi^+} > 213\ MeV/c$
- $BR(K^+ \to \pi^+\gamma) < 2.3 \times 10^{-9}\,(90\%\ CL)$
- $BR(\pi^0 \to \nu\overline{\nu}) < 2.7 \times 10^{-7}\ (90\%\ CL)$
- These are the most stringent limits available for these decay modes